Hydrological self-regulation of domed peatlands in south-east Asia and consequences for conservation and restoration

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SUMMARY

This article explores the hydrological constraints on the existence of forested peat domes (peat swamp forests) in the humid tropics, the self-regulation mechanisms that enable them to persist and the implications for restoration of damaged domes. The most important requirement for the preservation of peat is permanent saturation by water. The variable input of precipitation must be translated into a constant water supply to the peat mound. In intact tropical peat swamp domes, water is stored above the peat surface in depressions between hummocks that surround tree trunks and between spreading buttress roots. This above-ground water store is analogous to the water stored in the loose upper layer of peat and vegetation in *Sphagnum* bogs. The horizontal differentiation of the peat swamp forest floor into hummocks with limited hydraulic conductivity and depressions with high storage capacity resembles the hummock-hollow patterning of these *Sphagnum* bogs. Hummocks and other surface elements functionally resemble V-notch weirs that regulate water availability. Buttressed trees play a key role in providing the structural elements for hydrological self-regulation. An additional level of regulation is found in the concentric zonation of forest types with increased presence of buttressed trees on steeper margins. Conservation and restoration efforts should take into account the inter-relationships between trees, water and peat and the hydrological feedbacks that operate as a consequence.

KEY WORDS: bog, buttress roots, Indonesia, peatland hydrology, peatland restoration, tropical peat swamp forest, tropical trees.

INTRODUCTION

Most of the lowland peat swamps in south-east Asia are, in essence, raised bogs: ombrotrophic, dome-shaped landforms located on interfluvial divides (Anderson 1964, Figure 1). Molengraaff (1900) was the first to report explicitly on the existence of raised bogs in tropical south-east Asia. Describing the peatlands of the Madi Plateau (inland Borneo), he noticed how the peat was made up mainly of trees instead of the mosses and dwarf shrubs he knew from the raised bogs of the temperate zone. Polak (1933) studied and described in detail the domed, biconvex shape and the ombrotrophic nature of lowland tropical peatlands, further stressing their correspondence to temperate raised bogs.

Few people realise how special a raised bog dome is: it embodies the paradox "high and wet" (Dau 1823). In the raised bogs of the temperate and boreal zones close interactions between vegetation, peat and water operate as 'self-regulation' mechanisms that enable these domes to persist under varying climatic conditions for thousands of years (Joosten 1993). The apparent resilience of the coastal peat swamp domes of south-east Asia to Late Holocene climate variability (Dommain *et al*. 2009) suggests that similar self-regulatory forces control tropical peatland ecosystems.

More than a decade ago, Bragg (1997) suggested that there were parallels in hydrological functioning between temperate raised bogs and south-east Asian peat swamps. Additional data and insights have become available since. It is now possible to develop further the analogy between temperate and tropical domed peatlands and derive implications for management of the latter.

This paper explores whether mechanisms similar to those that operate in temperate raised bogs are responsible for sustaining tropical peat swamp domes. First, we focus on the peat that constitutes the dome and how it is preserved under permanent water saturation. Then we present fact-based hypotheses on how plants and litter may regulate water availability. Finally, we address the importance of these regulation and feedback mechanisms for peat swamp conservation and restoration.

THE PEAT DOME

In very simple terms, a peat dome can be described as a mound of peat (dead organic material) overlain

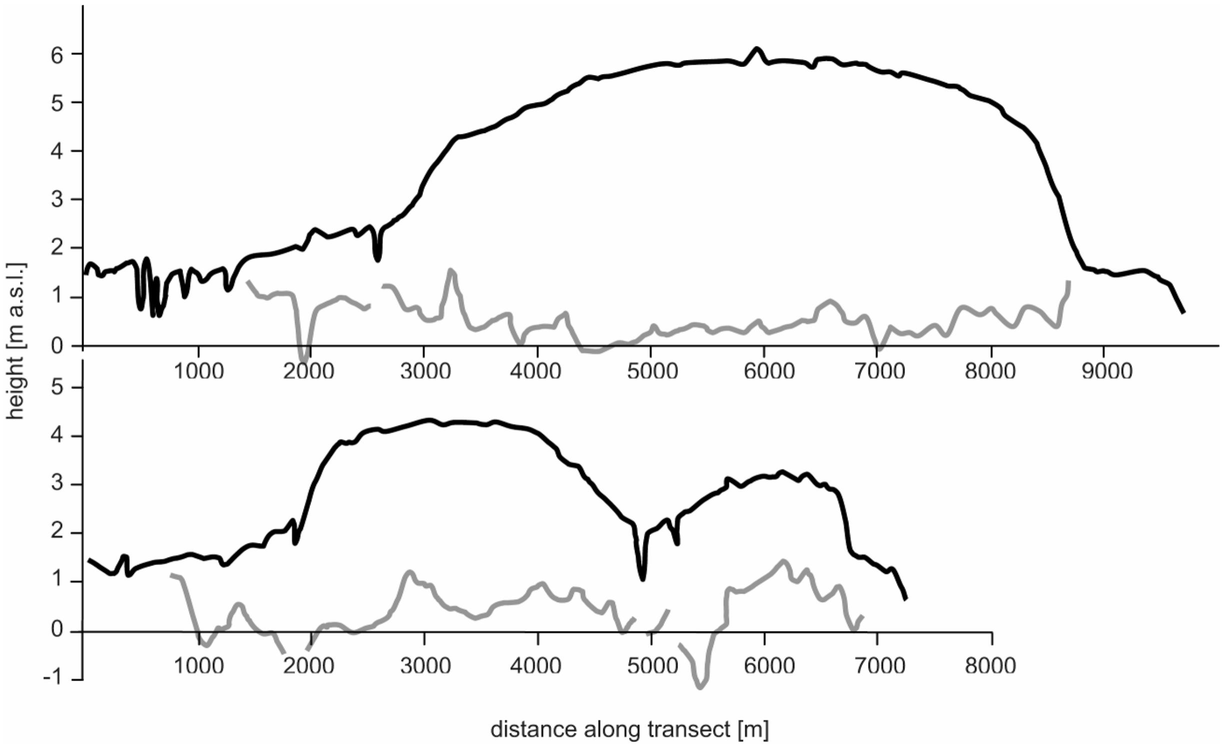

Figure 1. Cross-sections of peat domes in Borneo (after PS Konsultant 1998). Black lines denote the peat surface and grey lines the underlying mineral stratum. The domes are restricted in size by streams, in the lower example incising the dome.

by vegetation. The peat of the mound does not completely decompose so long as water saturation and consequent anoxic conditions prevail. However, permanent water saturation is not easily attained as - even in the absence of evaporation - water is continuously lost from the mound by gravity drainage. To maintain permanent water saturation these water losses have to be compensated by a continuous input of rainwater. The question is then *how much* water input from above is needed to keep the mound fully and continuously water-saturated. For a mound with a circular base and half-elliptic cross-section, this amount (U) can be derived from Equation 1 (Childs 1969, Huisman 1972, Ingram 1982, Bakker 1992):

$$\frac{U}{k} = \frac{2h^2}{R^2 - r^2} \qquad [1]$$

in which:

U = the rate of water input to the mound (m d^{-1});
k = the hydraulic conductivity of the peat (m d^{-1});
h = the height of the mound at point r (m);
R = the radius of the mound (m); and
r = the distance (m) from any point to the centre of the mound

This simple equation incorporates the following assumptions:

1. No water disappears into the mineral subsoil beneath the peat mound. This approximation is valid for tropical peat domes as the subsoil beneath them consists of mangrove clay or podsols with an impermeable hardpan layer (Anderson 1964, 1983, Bruenig 1974, 1990), or the peat is isolated from the mineral subsoil by sparingly permeable peat or strongly humified layers.
2. The hydraulic conductivity is uniform in all directions throughout the peat mound. This assumption may not apply to tropical peat domes (Ong & Yogeswaran 1992, Takahashi & Yonetani 1997; cf. Nughroho *et al*. 1997) but, as we shall see, inaccuracy here would not change our principal findings.

Let us take as an example a peat dome with a radius of 3 km and a summit height of 5 m. Equation 1 shows that, in order to keep a peat mound of these dimensions permanently wet, U/k must be 5.6 10^{-6} m d^{-1}. The required water input (U) can thus be derived if the hydraulic conductivity k is known. Reliable data for hydraulic conductivity (k) of tropical peats are still limited, particularly for deeper

Table 1. Hydraulic conductivity of tropical peatswamp forest peats.

Hydraulic conductivity (m/d)	Specifications	Reference
0.4	1.5 m below the surface	Takahashi & Yonetani (1997)
0.05 – 2.8		Nughroho *et al*. (1997)
9	estimated for uppermost 1 m of peat	Takahashi & Yonetani (1997)
0.5 – 28	fibrous woody peat	Ong & Yogeswaran (1992)
0.001 – 35	review of measurements in Sarawak peats	Ong & Yogeswaran (1992)
4 – 59	measurements, probably in upper peat layer	DID & LAWOO (1996)
30		Siderius (2004)
10 – 140	review of modelled values	Ong & Yogeswaran (1992)
200	derived from field observations	Hoekman (2007)
116 – 483	fibrous woody peat with preferred flow pathways	Ong & Yogeswaran (1992)

layers (Table 1). Applying a hydraulic conductivity value of 10 m d^{-1} we calculate a necessary water supply of only 5.6 x 10^{-5} m d^{-1} or 20 mm per year. If the hydraulic conductivity were lower or the radius larger, an even lower water supply would suffice. So, in a climate with several thousands of millimetres of annual precipitation, a peat mound apparently needs only a very small fraction of that amount to maintain itself (Hooijer 2005, Hoekman 2007). The question then arises: why aren't there many more peat domes in the humid tropics?

The preservation of the peat mound requires *permanent* water saturation, which implies that the small amount of water input - in our example 20 mm per year - has to be distributed *absolutely uniformly* over the year. If the water supply is irregular, during every moment that the peat mound is not fed with water, the water level will drop, the uppermost layer of peat will no longer be saturated, and the now aerobic peat will decompose. If an absolutely constant supply of water is not guaranteed, peat cannot persist and will eventually disappear.

Even in the humid tropical climate of south-east Asia it is *not* raining most of the time. Most of the peat swamp area of south-east Asia is in fact subject to marked dry spells. A distinct dry season is experienced in monsoon regions (Aldrian & Susanto 2003, Hendon 2003), and droughts of 30 days or more may also occur in coastal perhumid regions (Brunig 1969, Whitmore 1975, Walsh 1996, Harrison 2001). In southern Borneo, southern Sumatra, Java and the Lesser Sunda Islands the monsoon-governed dry season (May–September) is particularly strong; monthly mean precipitation may drop below 100 mm (Aldrian & Susanto 2003). During El Niño events, which recur every 2–10 years (Philander 1983). droughts are more extreme (Walsh 1996, Harrison 2001, Figure 2a, Figure 3a). Even in the wet season, dry spells spanning several days may occur (Figures 2a, 2b, 3a).

The varying weather conditions severely constrain peat formation and preservation because they induce large water table fluctuations. Consequently, a peat mound in the humid tropics also needs an interface between the reality of fluctuating water supply and the requirement for constant water saturation. The temporally varying precipitation and evapotranspiration must be transformed into a steady supply of water to the peat by a structure placed between the atmosphere and the peat. Such a structure on top of the peat mound must combine:

- a *limited horizontal hydraulic conductivity*, i.e. a resistance to water flow ensuring the retention of water that would otherwise immediately flow away after rain showers, and
- a *large storage capacity*, i.e. the storage of sufficient water to compensate for water lost from the mound by gravity drainage and evapotranspiration during rain-free periods.

Limited hydraulic conductivity requires the presence of densely packed material with little interspace. Such material leaves little room for water storage, however. Thus these requirements seem diametrically opposed. The solution to the dilemma is found in passive spatial and/or active temporal division of the contrary tasks.

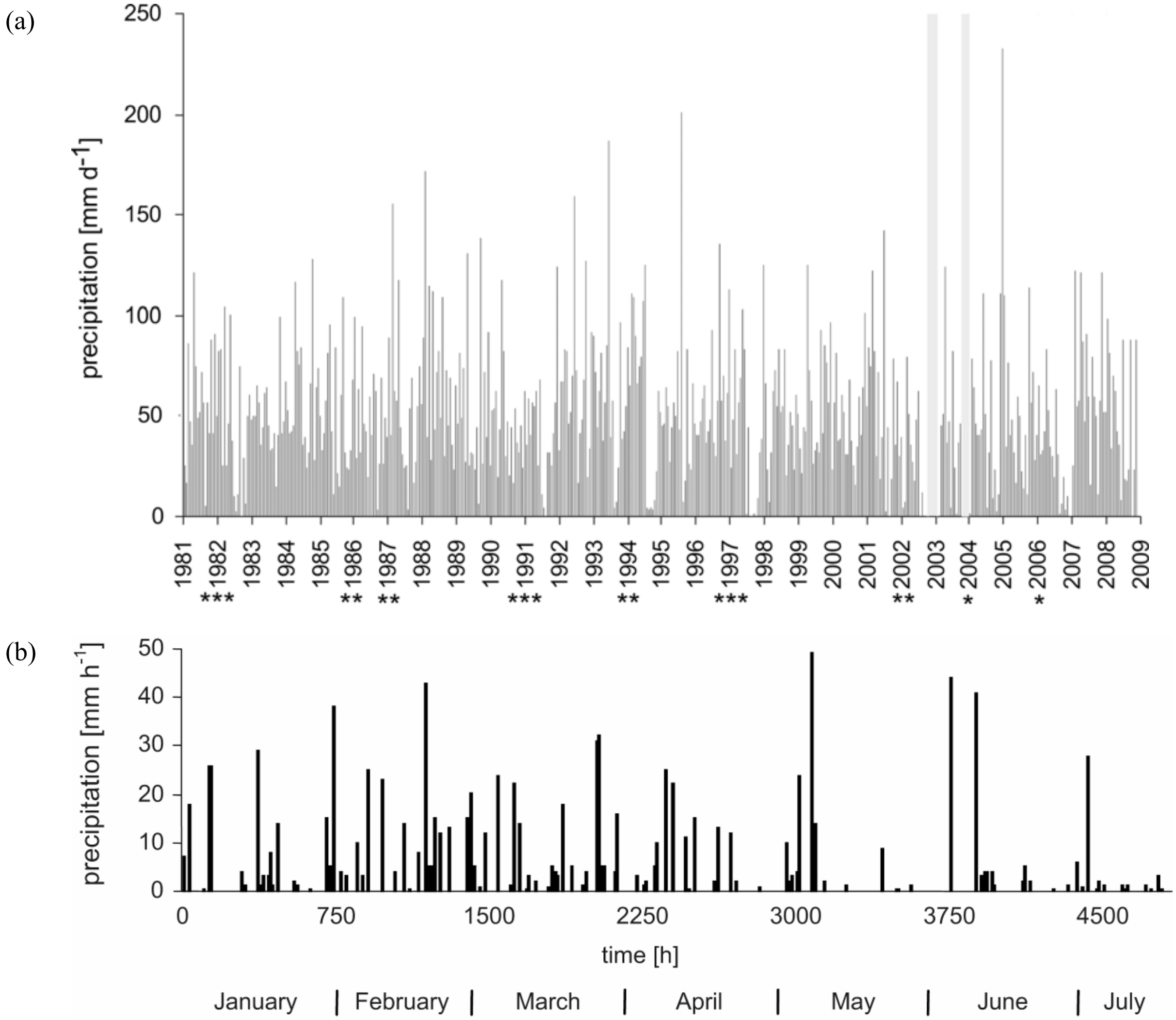

Figure 2. Precipitation data for Palangka Raya, Central Kalimantan, Indonesia: (a) daily rainfall between 1981 and 2009, shaded areas indicate data gaps in 2002 and 2003, asterisks denote *weak, **moderate and ***strong El Niño years; (b) high resolution (6-hourly) data for January–July 2005 (abscissa = hours after 00:00 hrs on 01 January 2005), data from NOAA National Climatic Data Center.

SURFACE STRUCTURES

In *Sphagnum* bogs of the boreal and temperate zones the upper layer of loose moss biomass and scarcely decomposed peat combines a limited hydraulic conductivity - which restricts drainage - with a high storage capacity which restricts water level fluctuations and facilitates the small but continuous supply of water to the denser underlying peat mound. In addition, the upper layer displays a coarser-scale horizontal differentiation. Limited hydraulic conductivity and a large storage capacity are also combined in a hummock-hollow surface pattern where dense and higher hummocks stagnate the flow of water and hollows store the surplus. The random configuration of hummocks and hollows can develop into regular string-flark surface patterns aligned perpendicular to the water flow, which further increases water storage (Couwenberg 2005).

In addition, a temporal separation of limited hydraulic conductivity and large storage capacity is realised in the upper layer of a *Sphagnum* bog. In this upper layer decomposition and collapse of the peat matrix result in decreased pore space, lower hydraulic conductivity and consequently less discharge. Addition of fresh material to the top continually replaces the lost coarse pore space and restores high storage capacity (Couwenberg & Joosten 1999). The result is a distinct vertical gradient in pore space and hydraulic conductivity

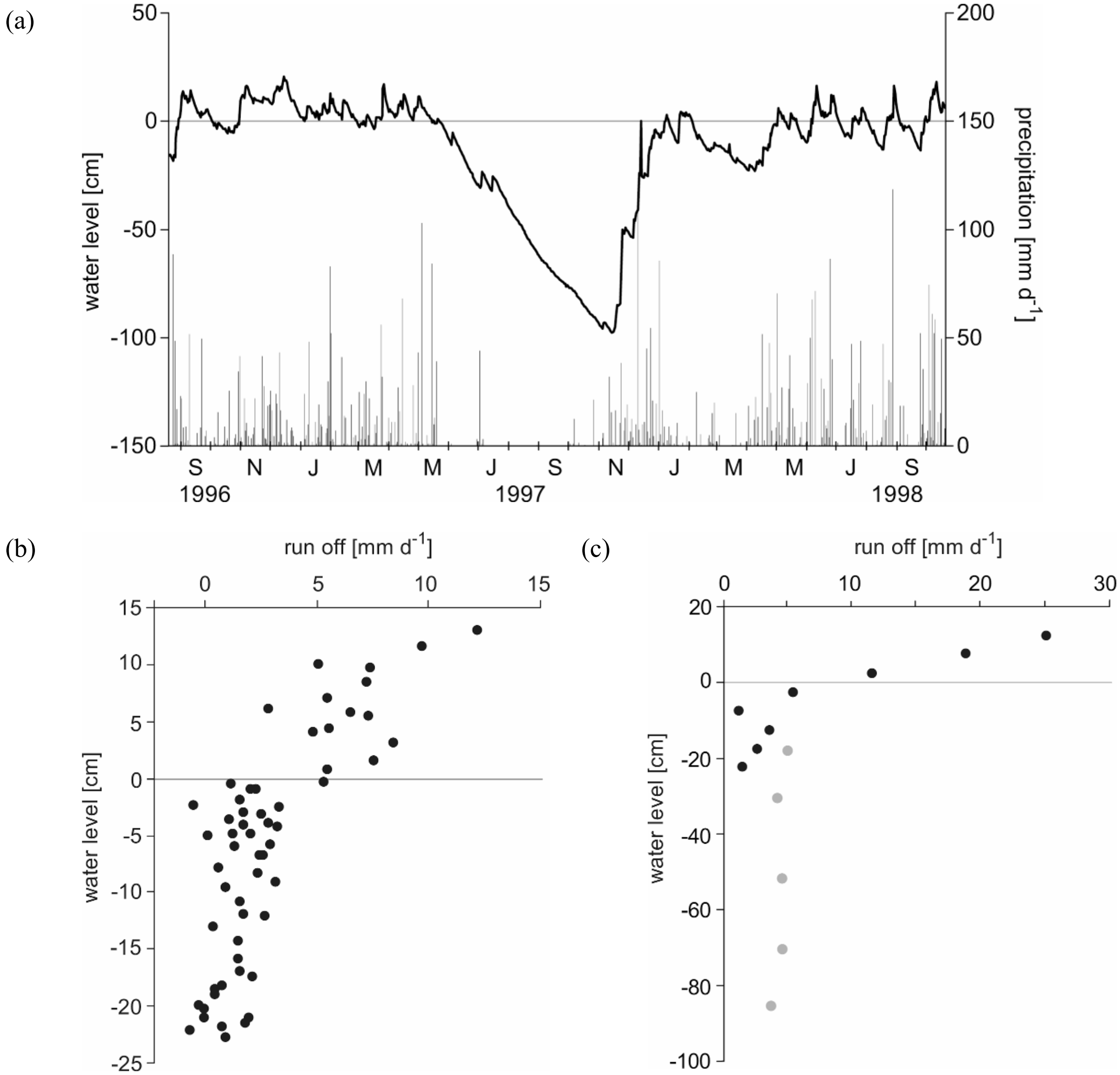

Figure 3. Hydrological data for an area of pristine peat swamp forest near Palangka Raya, Central Kalimantan: (a) water levels and precipitation in 1996–1998, after Takahashi *et al.* (2000) (note that 1997 was a strong El Niño year); and relationships of water level during days without rainfall with (b) runoff from March 1998 to February 1999 (after Kayama *et al.* 2000), and (c) runoff in June–October 1997 (●) and March–October 1998 (●) (after Takahashi *et al.* 2000). The datum level (zero on the vertical axes) is the ground surface.

(functionally similar to a V-notch weir, Clymo 1991). At high water levels, discharge through the more open structure at the top is rapid, regulating peak discharge and preventing erosion. As the water level is lowered, discharge occurs through the progressively smaller pores of deeper, more decomposed material (Ivanov 1953, 1981). Moreover, at lower water levels the loss of surface-layer buoyancy causes an increase in effective stress on the underlying water-saturated peat layers, which further compacts the peat and reduces hydraulic conductivity (Price 2003). The uppermost layer thus provides, by negative feedback, a self-regulation mechanism that limits the amplitude of water table fluctuations under varying meteorological conditions and guarantees the constant water supply that the underlying peat mound needs.

In domed tropical peat swamps we find trees growing on hummocks of root material and litter. Particularly large hummocks (> 0.4 m high) establish around buttressed trees (Shimamura & Mimose 2005, 2007; Figure 4). Spreading plank

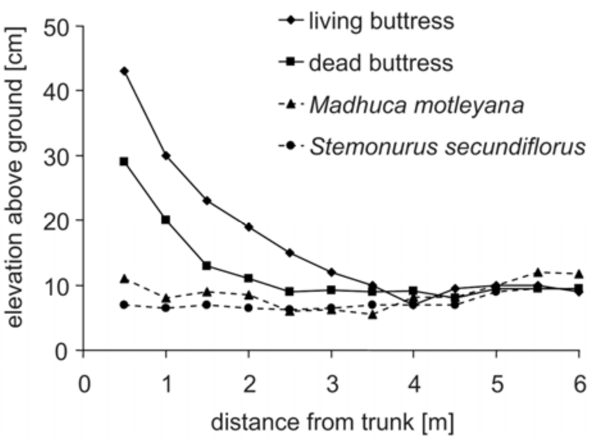

Figure 4. Change in surface height with distance from living established and dead buttressed trees and from trees of two non-buttressed species (after Shimamura & Momose 2007).

buttresses are additional elements that restrict the movement of water across the forest floor (Herwitz 1988, Takahashi *et al*. 2000, Kayama *et al*. 2000, Figure 5). In this way runoff is retarded and water is stored in depressions between hummocks and behind buttresses (Herwitz 1988). This pattern of live and dead plant material and the general surface roughness result in large amounts of water being withheld in depression storage and surface detention. The peat swamp forest floor and the lower part of the above-ground vegetation thus fulfil the combined but horizontally separated tasks of limited hydraulic conductivity and high storage capacity. In undisturbed peat swamp forests the water level remains above the surface for most of the year (Anderson 1964, Ong & Yogeswaran 1992, Takahashi *et al*. 2000, de Vries 2003, Hooijer 2005; Figure 3). As in *Sphagnum* bogs of the boreal and temperate zone, water level fluctuations in tropical peat swamps are largely restricted to an uppermost layer; in this case composed of above-ground roots, litter and vegetation and the depressions between them. The peat underneath this layer is kept permanently wet.

Aerobic decay on the forest floor is rapid (Brady 1997, Chimner & Ewel 2005, Yule 2008), whereas below-ground anaerobic decomposition of the more recalcitrant material is low (cf. Miyajima *et al*. 1997, Jackson *et al*. 2008, Couwenberg *et al*. 2010). As a consequence, no V-notch structure develops in the upper peat layer. Instead, a gradient of hydraulic conductivity is created above the ground surface (cf. Bragg 1997, Hoekman & Vrielink 2007; Figure 3b, c) by litter and vegetation including buttress roots (Shimamura & Momose 2005, 2007; Figures 4, 6). The lower the water level drops, the more runoff is obstructed. While low water levels lead to decomposition, too-high water levels would prevent peat swamp forest trees from growing and lead to excessive surface runoff, causing erosion. In order to maintain the dome it is, therefore, imperative to weaken the velocity and force of surplus runoff water (Evans & Warburton 2007). The gradually widening V-notch of the above-ground hummocks and buttress roots results in diffuse drainage that discourages convergent flow and prevents the development of erosion channels (Figures 4, 6).

Thus, the major difference between *Sphagnum* bogs of the boreal and temperate zone and peat swamp domes in the tropics is that in the former the most important zone for hydrological regulation and the zone of peat formation coincide (Clymo & Pearce 1995), whereas in the latter these zones are spatially separated. Peat formation in tropical peat swamps - as in grass and sedge fens in the temperate and subtropical zones - largely takes place as ‘replacement peat’ by roots growing into permanently waterlogged layers (Esterle & Ferm 1994, Brady 1997, Prager *et al*. 2006).

ZONATION

A dome shape implies a near-horizontal centre and progressively increasing surface gradient towards the edges. In boreal and temperate raised bogs, this results in a concentric arrangement of distinct vegetation and micro-relief patterns (Couwenberg & Joosten 2005). In the flatter centre, wetter conditions favour the establishment of more permeable elements that readily permit water flow (Bakker 1992) and compensate for the effect of the small slope, a negative feedback. Towards the margins, drier conditions favour less permeable elements that impede lateral runoff - again a negative feedback (Couwenberg & Joosten 1999, 2005).

An analogous pattern is found in the concentric arrangement of plant communities in the tropical peat swamp forests of south-east Asia (Anderson 1983, Bruenig 1990, Shepherd *et al*. 1997, Yamada 1997, Page *et al*. 1999, Momose & Shimamura 2002). Going from the margin towards the centre of a tropical peat dome, large and abundant buttresses become smaller and rarer (Anderson 1983, Bruenig 1990, Yamada 1997, Page *et al*. 1999). The sloping rand of a peat dome is dryer, water table fluctuations are larger and nutrient availability is higher than in the interior (Anderson 1983, Esterle & Ferm 1994, Page *et al*. 1999). Under these conditions, buttressed trees establish and grow to substantial height. Buttress roots stabilise, and thus provide a competitive advantage for, shallow-rooted trees (Ennos 1993, Crook *et al*. 1997). In addition,

Figure 5. Spreading buttress roots reduce surface runoff and cause ponding of water. Tanjung Puting National Park, Central Kalimantan, April 2008. Photo: René Dommain.

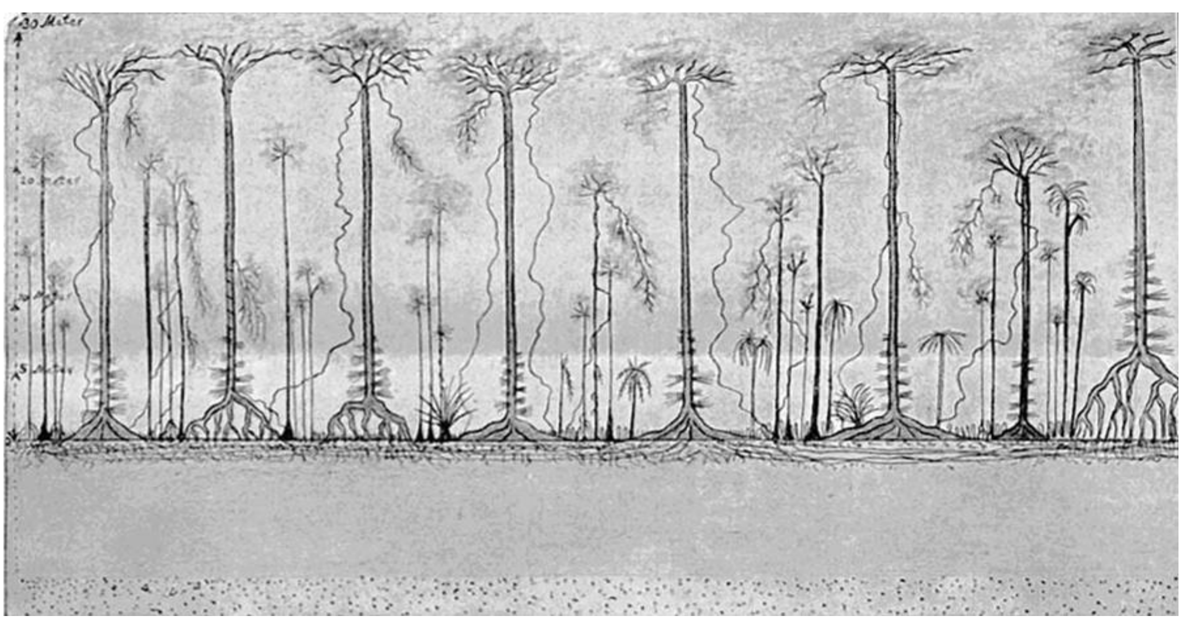

Figure 6. Vegetation in the peatland near the 20/21 March camp, as seen by the Dutch botanist Sijfert Koorders during the 1891 IJzerman expedition through Sumatra (IJzerman *et al*. 1895, Potonié 1907) with explicit V-notch-structures at the surface, formed by the buttressed bases of the tree trunks and by stilt roots.

buttresses disperse stemflow during heavy rainfall, averting erosion at the tree base and promoting infiltration of the nutrient-rich stemflow water within reach of the tree's own root system (Herwitz 1988). As a result, buttressed trees grow taller than their neighbours. Taller trees are subject to wind stress, which further stimulates the expansion of buttresses (Richter 1984, Ennos 1993). Buttressed trees prompt the formation of hummocks which, in turn, promote the establishment of buttressed trees (Shimamura & Momose 2005); and water ponding upslope of buttresses and hummocks suppresses the establishment of competing buttress-forming species in the close vicinity (Shimamura *et al.* 2006). This feedback explains the higher aerodynamic canopy roughness observed in the forest on the sloping margin of the dome (Anderson 1983, Bruenig 1990, Yamada 1997). Canopy roughness increases wind stress, stimulating the expansion of buttresses and consequently a decrease in surface runoff. This response of the vegetation and surface micro-relief to drier conditions thus provides a negative feedback to the drier conditions.

In response to long-term water level changes, the proportion of hummock-forming buttress trees to non-hummock-forming trees is likely to alter (Shimamura & Momose 2005, 2007, Shimamura *et al.* 2006). Buttress-forming trees, because of their general flood intolerance, respond to rising water levels with reduced recruitment (Shimamura *et al*. 2006) and probably also with lower growth rates or even dieback, while flood tolerant non-mound-forming trees are favoured. Such a change in vegetation increases horizontal hydraulic conductivity, mitigating the effect of increased water input or decreased water losses. Under drier conditions, buttress-forming trees may establish also in depressions (Shimamura *et al*. 2006) and outcompete flood-tolerant species, thus increasing the density of stagnating structures on the peat surface, which will moderate the lowered input or increased loss of water.

Moving towards the centre of the tropical peat swamp dome, the water table is generally closer to the surface and flooding is more frequent and persistent, making species with stilt roots and pneumatophores (e.g. knee roots) more competitive (cf. Richards 1952, Corner 1978, Wittmann & Parolin 2005). These adaptive root formations obstruct water flow less than the buttresses on the dome margin, thereby allowing better lateral drainage. In conclusion, the flat and wet central area is dominated by forest types that readily permit runoff, whereas lateral water losses on the sloping, drier margin are limited through increased representation of tree species that form buttresses and hummocks.

VEGETATION

In temperate and boreal raised bogs, only a handful of the *ca*. 300 moss species of the genus *Sphagnum* in existence (Michaelis in press) are able to shape a continuously renewing upper peat layer that combines a small hydraulic conductivity with a large storage coefficient (Joosten 1993). The effectiveness of these few species is illustrated by the wide distribution of *Sphagnum* raised bogs.

In contrast, the occurrence of tropical ombrogenous domed peatlands is much more limited. Of the 12.5 million km^2 of humid tropics in the world (Schultz 2005), less than 1% is covered by peat swamp domes, almost exclusively in south-east Asia. Some 165,000 km^2 of forested peatland exists in tropical Africa and South America (Joosten 2009), but ombrogenous peat domes of similar extent and thickness have not yet been described from these continents in spite of seemingly suitable climatic, geological, and geomorphological conditions (IMCG Global Peatland Database www.imcg.net/gpd/gpd.htm, Whitmore 1975, Sieffermann 1988). There are some large mounds of ombrogenous peat in the coastal plain of Surinam and French Guiana, but their maximum thickness is only 2.5 m (Brinkman & Pons 1968). Lähteenoja *et al*. (2009) report the occurrence of ombrotrophic peat domes of similar thickness from Peruvian Amazonia. Domed forested peatlands may prove to cover large tracts of the Congo basin interfluves (cf. Campbell 2005), but hardly anything is known about them.

Several of the dominant peat swamp forest taxa of south-east Asia are endemic to this region, including the genera *Shorea*, *Gonystylus*, *Dactylocladus*, *Swintonia*, *Madhuca*, *Palaquium* and *Parastemon*. Trees of these taxa may play a decisive role in the formation and maintenance of peat swamp domes (cf. Whitmore 1975). The role of these taxa may be similar to that of the few key *Sphagnum* species in boreal and temperate bogs. On the other hand, tree species adapted to oligotrophic waterlogged conditions occur also elsewhere in the tropics (Richards 1952, Bruenig 1990) and display similar morphological adaptations such as buttressed roots. Possible differences in the recalcitrance to decomposition of the plant material (cf. Hedges *et al*. 1985) may explain why extensive tropical peat swamp forests have been found only in south-east Asia. We are, however, not aware of any comparative research into this issue. On the other hand, the apparent restriction of extensive peat domes to south-east Asia may rather result from peculiarities of Holocene landscape, climate and sea level evolution in the Sunda region (Anderson 1964, Sieffermann *et al.* 1987, Dommain *et al*. 2009).

HYDROLOGICAL SELF-REGULATION

Besides its v-notch structure and vegetation patterning and zonation, a living tropical peat swamp may possess various other hydrological self-regulation mechanisms that guarantee a more or less stable water table. These mechanisms function over a varying range of spatial and temporal scales. In *Sphagnum* bogs of the Northern Hemisphere (and Tierra del Fuego), a whole series of regulation mechanisms has been identified (Joosten 1993, Couwenberg & Joosten 1999, Couwenberg *et al.* 2005). Table 2 explores whether equivalent mechanisms exist in domed tropical peatlands and lists related research needs.

Albedo change, surface oscillation and intraspecific changes in plant growth form (Table 2) will function over the short term, i.e. on sub-annual to decadal timescales. Changes in composition, shape and configuration of vegetation and relief elements may constitute important self-regulation mechanisms on a decadal to centennial timescale. Changes in the spatial configuration of the surface elements over time stabilise against broad-scale changes in the hydrological boundary conditions.

Detailed palaeo-ecological investigation could unfold such spatio-temporal dynamics for past periods of strong climate variability, whereas dynamic forest models with an integrated hydrology component could simulate these feedback mechanisms and identify thresholds that trigger them under different climate scenarios.

RESTORING SELF-REGULATION

The challenges to be faced in restoring severely disturbed peatlands to living peatswamp forests are enormous. Deforestation and fire destroy the vegetation, which is the regulating structure that maintains the hydrological conditions needed to sustain the peat body. Furthermore, the removal of vegetation cover leads to increased soil surface temperatures and faster peat decomposition (Brady 2004, Ali *et al*. 2006, Ludang *et al.* 2007). Drainage also leads to subsidence with the strongest subsidence occurring along the ditches and canals, thus promoting erosion and the formation of explicit 'mini domes' (Hooijer *et al*. 2008), which frustrates re-wetting of large areas. Severe fires may remove large parts of the peat body (Usup *et al*. 2004). Flooding of repeatedly burnt areas hampers re-establishment of trees (Giesen 2004, Van Eijk & Leenman 2004, Wösten *et al.* 2006).

Crucial for restoration is the awareness that in peatlands plants, water and peat are mutually interdependent. The plants determine the surface hydrology and the hydraulic properties of the peat that is formed. Water levels determine which plants will grow, whether peat will be accumulated and stored, and how strongly decomposed it will be. The plant cover and peat structure determine how the water will flow and how the water level will fluctuate. These close interrelations imply that when any one of these components is degraded, the others will also deteriorate. Not necessarily all at once, but in the longer run inevitably.

Selective logging alters species composition and therewith organic matter supply to the peat body (Brady 2004). More importantly it renders the hydraulic structure of the vegetation more 'open', most significantly along the dome margins where large trees with buttresses, which are essential for hydrological self-regulation, are preferentially removed. Restoration should focus on protecting and re-establishing these species. If hydrology has been altered by (often illegal) selective logging and the construction of narrow and shallow canals for transporting the logs, the canals must be closed.

When vegetation and hydrology are severely altered, up-to-date three-dimensional models with small contour interval must assess whether a hydrologically viable shape is still present, will spontaneously re-develop (e.g. by decomposition of too-dry protuberances), or can easily be restored. Based on such models and on data on local climate and hydraulic conductivity, surface flow paths with their specific discharge rates have to be identified in order to place dams in the most effective way (Edom *et al*. 2007). With respect to dam placement it is important to think in terms of coherent systems rather than of single dams. One should keep in mind that enormous volumes of water *have* to leave the dome, even in pristine peat swamp forest. It is thus senseless to make dams fully impermeable and to dam up as much water as possible. Restoration measures should be designed to allow the surplus water to leave the dome without causing damage (Ritzema & Wösten 2006), while retaining a sufficient store for drier periods. Canal blocks should force the water to spread out over the surface of the peatland to re-wet as wide an area as possible. This approach will often mean that a dense network of cascading dams with small head differences must be constructed (Ritzema & Wösten 2006, Edom *et al.* 2007). To disperse the water, damming should proceed centripetally starting from the centre of the dome. By spreading the water over the largest possible area, flow velocity and erosive power are reduced, flood-tolerant plants (e.g. *Pandanus* spp., *Combretocarpus rotundatus*) can re-establish more easily in the channels (self-recovery by terrestrialisation), and pressure on downstream dams decreases (Edom *et al.* 2007).

Table 2. Self-regulation mechanisms in domed *Sphagnum* bogs and possible equivalents in tropical peat swamp forest domes, together with an estimate of how important each one might be in tropical peat domes.

Mechanism	*Sphagnum* bog	Tropical peat dome	Potential importance in tropical peat domes
Evapotranspiration control	Increase in surface albedo (reduces evaporation by reflecting heat) due to *Sphagnum* capitula turning white when suffering water shortage (Eggelsmann 1963, Harris 2008).	Leaf shedding during severe droughts (less than 100 mm rain month^{-1} and at least two weeks without rain; Goldammer 2007).	Most short-term control of evapotranspiration by tropical peat swamp trees will rely on stomatal behaviour.
Surface oscillation (*Mooratmung*)	Reversible swelling and shrinking of peat with changing water supply between seasons reduces water level fluctuations relative to the surface (Weber 1902, Whittington *et al*. 2007, Fritz *et al*. 2008). Changes in water level furthermore coincide with immediate changes in pore space and hydraulic conductivity (Price 2003).	Surface oscillation up to 2 cm observed in the Mawas peatland (Central Kalimantan; Hoekman & Vrielink 2007); drainage-related drying of peat is partly reversible (Salmah *et al*. 1992).	Likely to be less intense than in *Sphagnum* bogs. Also likely to be less important in peat swamps because woody material will make peat structure more resistant to elastic changes.
Intraspecific changes in growth form	Growth form and thus hydrological characteristics of a single species of *Sphagnum* change with changing water level, giving better capillarity and lower permeability in dry locations and conditions (Joosten 1993, Couwenberg *et al*. 2005, Baumann 2006).	Size and extent of buttresses changes along hydrological gradients, for instance in *Shorea albida* (Anderson 1983, Bruenig 1990).	Requires further study, particularly with respect to whether intraspecific changes in morphology represent negative or positive feedbacks to changing hydrological site conditions.
Changes of species, vegetation types and micro-relief structures	Different *Sphagnum* species with different growth forms occupy different hydrological niches (e.g. Overbeck & Happach 1957, Ratcliffe & Walker 1958, Luken 1985, Rydin 1993, Rydin *et al.* 2006) and have different hydraulic properties.	Wide variation in tree growth forms, floristic composition and of micro-relief elements along hydrological gradients (Anderson 1983, Yamada 1997, Page *et al.* 1999, Shimamura *et al*. 2006, Shimamura & Momose 2007).	Detailed palaeo-ecological studies may reveal temporal dynamics in relation to changes in site conditions. Quantitative research into feedback mechanisms and further inventories of species and their morphological traits is needed.

(continued)

Table 2 continued

Mechanism	*Sphagnum* bog	Tropical peat dome	Potential importance in tropical peat domes
Microtope pattern	Arrangement of elongated drier hummocks and wetter hollows perpendicular to the slope increases efficiency of hydrological regulation. Wetter elements store water whilst drier ones impede runoff (Couwenberg & Joosten 1999).	Hummock coalescence to form ridges has been described (Yonebayashi *et al.* 1997) and patterns of large stripes are visible in the Baram peat dome between the Baram and Bakong Rivers in northern Sarawak (Anderson 1983, Bruenig 1990).	Formation of such explicit patterns is less likely on tropical peat domes because of their rather gentle slopes, the large water level fluctuations and the smaller difference in hydraulic conductivity between hummocks and hollows (cf. Couwenberg 2005). In many areas, any natural patterns may already have been obliterated by drainage, logging or natural degradation.
Mesopattern	The increasing surface gradient from the centre to the margins of the dome is reflected in concurrent decreasing wetness and hydraulic conductivity of distinct concentric zones. Changes in size and shape of the dome affect the extent of these zones (Couwenberg & Joosten 2005).	Concentric zonation of forest types, with flood-tolerant species dominating the centre and buttressed trees more abundant towards the edges (Anderson 1964, 1983, Bruenig 1990, Page *et al*. 1999).	Needs quantitative hydrological research.
Limit to dome size	With increasing width, the dome becomes flatter and thereby wetter, increasing the likelihood of bog-burst. Surface area increases quadratically in relation to bog diameter, whereas circumference increases linearly. If concentrated water discharge then creates an incision in the peat dome, the original dome cannot persist and splits into two smaller parts (Masing 1972, Couwenberg & Joosten 1999).	Landslides are known to occur in peatswamp forests (Lee & Pradhan 2007), but descriptions are rare. Wilford (1966) reports a landslide in a peat swamp in Sarawak. Dividing blackwater streams are common (Figure 1).	Probably important, especially through time.

Overflow provisions in dams intended to prevent the development of erosive flow paths around them may introduce the drawback that water flow is concentrated and the drainage base remains too low. Preferential channelling around the dams must be restricted by extending them sidewards and encouraging a protective sward of vegetation to re-establish.

In deforested areas and severely degraded forests, the structure that provides hydrological regulation under natural conditions has been removed and runoff is too rapid due to lack of surface resistance. Thus, water drains away too quickly in the wet season, leaving the surface peat dry and prone to decomposition during the dry season. To keep the surface permanently wet, depression storage and surface detention must be established by stimulating the development of vegetation that can effectively reduce water discharge. Pioneer species like ferns may not slow down water flow sufficiently, whereas seedlings of the necessary buttressed trees germinate and survive only on hummocks (Yonebayashi *et al.* 1997, Shimamura & Momose 2007) and cannot cope with the harsh conditions that prevail after degradation and re-wetting (Giesen 2004, Van Eijk & Leenman 2004, Wösten *et al.* 2006). Thus, in addition to blocking the canals, restoration should re-introduce buttressed trees by creating hummocks and re-plant areas where surface slopes lead to too-rapid runoff. Intensive hydrological assistance over prolonged periods may be necessary.

Because common agricultural activities such as oil palm and *Acacia* cultivation require lowered water levels, the allocation of different parts of a single peat dome to different land uses will frustrate attempts to restore the hydrological integrity of the peatland. Drainage canals will reduce the potential height of the water table mound that sustains the peat dome (cf. Glaser *et al*. 2004, Equation 1), slowing or halting peat formation even in zones that are allocated to conservation and not directly drained. Furthermore, the associated migration of the water divide towards its new equilibrium point will render areas elsewhere on the dome no longer saturated with water and thus also subject to peat losses (cf. Glaser *et al*. 2004).

When the shape of the peatland is so disrupted by drainage, oxidation and fire that there is no prospect of restoring one or more (new) self-sustaining *living* peat domes, the focus must be on slowing down peat oxidation and preventing fire by re-wetting the peatland as completely as possible. As buttress-forming tree species are unlikely to have sufficient capacity for re-wetting under such conditions, it may be necessary to construct artificial ridges perpendicular to the slope to retain wet-season runoff (cf. rice terraces). The challenge for such severely degraded areas is to develop and implement land use systems that combine economic benefits with maximal re-wetting.

The management principles described above should not be misconstrued to suggest that restoration of degraded peat domes is reasonably simple; this would give a totally false impression. The fact that large supplies of rainwater and sophisticated self-regulation processes are necessary to guarantee even a minimal constant water supply to the peat mound illustrates the improbability of peat swamp dome existence and the consequent difficulties of restoration. That their resilience against changes in climate and vegetation is not unlimited is underlined by the ongoing degradation of the peat domes in inland Central Kalimantan which have already been degrading for more than a thousand years (Sieffermann *et al*. 1988, Dommain *et al*. 2009).

As peat domes with limited or no damage are already extremely rare in south-east Asia - if they persist at all (Miettinen & Liew 2010a, b) - high priority must be given to conserving any surviving examples, and to restoring domes that still have good potential for reinstatement as self-regulating peat accumulating entities. It is imperative that such areas are rapidly identified and adequately protected, restored and managed (cf. Wetlands International 2010).

Peat must be retained not only in conservation areas but also in agricultural and forestry areas in order to avoid sustained CO_2 emissions (Couwenberg *et al*. 2010) and increased risk of flooding and loss of fertile soil. Thus, for areas that cannot be maintained or restored to living peat swamp forest, the challenge is to develop and implement management techniques that combine economic benefits with minimal impact on the remaining environmental functions of the peatland (Brady 2004, Joosten & Augustin 2006, Wichtmann & Joosten 2007). Although such 'paludicultures' such as wet agriculture, wet forestry and pisciculture may not yet be fully profitable, they will become so when the functions of carbon storage and avoidance of CO_2 emissions are monetarised and appropriately remunerated (cf. Butler *et al*. 2009).

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