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Carbon storage capacity of tropical peatlands in natural and artificial drainage networks

Alexander R Cobb①, René Dommain②,④, Fangyi Tan②, Naomi Hwee En Heng①,⑥ and Charles F Harvey①,⑤

1 Center for Environmental Sensing and Modeling, Singapore-MIT Alliance for Research and Technology, Singapore 138602, Singapore
2 Institute of Geosciences, University of Potsdam, 14476 Potsdam, Germany
3 Human Origins Program, National Museum of Natural History, Smithsonian Institution, Washington, DC 20013, United States of America
4 Nanyang Technological University, Asian School of the Environment, Singapore 639798, Singapore
5 Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, United States of America

E-mail: alex.cobb@smart.mit.edu

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Abstract

Tropical peatlands store over 75 gigatons of carbon as organic matter that is protected from decomposition and fire by waterlogging if left undrained. Over millennia, this organic matter builds up between channels or rivers into gently mounded shapes called peat domes. Measurements of peat accumulation and water flow suggest that tropical peat domes approach a steady state in which the peat surface morphology is described by a uniform curvature, setting a limit on the carbon that a peatland can store. We explored the maximum amount of carbon that can accumulate as water-saturated peat in natural and artificial drainage networks of northwest and southern Borneo. We find that the maximum volume of peat accumulation in a channel-bounded parcel is proportional to the square of the parcel area times a scale-independent factor describing the shape of the parcel boundary. Thus, carbon capacity per area scales roughly with mean parcel area in the peatland. Our analysis provides a tool that can be used to predict the long-term impacts of artificial drainage, and to devise optimal strategies for arresting fires and greenhouse gas emissions in tropical peatlands.

1. Introduction

Tropical peatlands are estimated to store over 75 Gt carbon [1–4], preserved as peat where decomposition of woody organic matter is slowed by waterlogging [5]. Analogous ecosystems of the Carboniferous and Miocene created some of the world’s largest deposits of coal [6, 7], and many extant peatlands have continuously sequestered carbon for 5,000 years or more [8, 9], thereby exerting a cooling effect on the global climate system [10, 11]. However, in the last 30 years, artificial drainage of tropical peatlands for agriculture has been rapidly releasing this carbon via organic decomposition [12–14] and fire [15, 16]. Decomposition and fires in drained peatlands of Southeast Asia are now a major source of greenhouse gas emissions [13] and transboundary smoke haze [15, 16], having released about 2.5 Gt C since 1990 [13] and exposed millions of people to unhealthy levels of airborne particulates [17, 18]. Tropical peatlands of Africa [3] and the Americas [2] could become similarly vulnerable if drained [19]. Because drainage has led to large emissions, restoration of tropical peatlands by blocking artificial drainage networks has been proposed as a cost-effective way to help meet climate targets [14, 20, 21]. Planning the restoration of tropical peatlands and understanding their role in Earth’s carbon cycle require an understanding of how much carbon peatlands can preserve by waterlogging, and how it is affected by the geometry of natural and artificial drainage networks.

In tropical peat domes, peat can remain waterlogged in deposits that rise over 10 m above the water level in their bounding channels [22] because water that drains to dome margins is replaced by rainfall [5, 23–25]. Nonetheless, a peat dome cannot grow
in height indefinitely, because if peat is piled too steeply, the surface peat cannot remain waterlogged and will decompose. Thus, the maximum height of a peat dome is limited by the size and shape of the channel-bounded parcel on which it accumulates. In the 20th century, this constraint was explored in raised bogs, which are analogous to tropical peat domes, through analyses of peatland hydrology and peat accumulation [26–29]. These analyses predict the profile of equilibrium peat elevation in a cross-section through a bog, assuming that the boundaries of the bog are long, straight lines formed by two parallel rivers [28, 29], as may occur, for example, in post-glacial landscapes [30, 31]. These assumptions do not apply where boundaries created by drainage networks are complex, and thus these profiles cannot directly predict overall limits on peat accumulation in most drainage networks.

In earlier work [25], we derived a model for the limiting morphology of tropical peat domes with boundaries of any size or shape. The model is based on field measurements showing that flow in tropical peatlands occurs predominantly in the loose-structured matrix of peat near the surface, where conductivity is very high [32, 33], so that the efficiency of flow through the peatland, or hydraulic transmissivity, varies greatly in time but is approximately independent of peat thickness. Using this approximation, we showed that the limiting morphology of a tropical peat dome satisfies Poisson’s equation, in which the curvature $\kappa$ of the peat surface is uniform throughout the peatland (figure 1). This prediction was validated by collecting radiocarbon dates from a peat dome in Brunei Darussalam Darussalam, showing that the dome was at or near carbon equilibrium where it conformed to this limiting morphology. However, the analysis examined part of just one of many domes in the drainage network, and did not examine the overall limits on carbon storage imposed by the geometric shape and size of parcels in the peatland.

Over half of the tropical peat landscapes in Peninsular Malaysia, Sumatra and Borneo have been further partitioned by canals and ditches [34] primarily because crops such as oil palm [35] and acacia require that surface peat is dry. Ditch spacing in plantations is designed to ensure that the maximum water level in the peat is close to the water level in ditches [35, 36]. This criterion implies that the maximum height of waterlogging above the drainage network in plantations, and therefore the limiting peat height, is small. However, drainage in tropical peatlands has generally been evaluated not by its effect on the capacity of the peatland to store carbon, but by rates of peat thickness loss or carbon emissions. Data on peat thickness loss per time, peat carbon density, and typical water levels are used to derive emission factors for different land cover classes, which are then multiplied by land cover area to derive regional estimates of emissions [13, 20, 37–40]. The emission factor approach provides a snapshot of overall rates of peat loss in drained peatlands, but it does not attempt to predict changes in peatland morphology, which control the long-term evolution of carbon emissions.

In this paper, we apply the analysis developed by Cobb et al [25] to examine how morphology and the long-term capacity for carbon storage are constrained in peatland landscapes. We describe the boundaries of parcels created by natural and artificial drainage networks at sites in northwest and southern Borneo, and solve Poisson’s equation in each parcel to analyze how distributions of parcel shape and size control the potential for peatland carbon storage. To illustrate how our approach can be used to evaluate the effects of land management decisions, we also calculate the long-term impact of a canal on the morphology and carbon storage capacity of a peat dome in northwest Borneo. Our analysis shows that fires and greenhouse gas emissions from Southeast Asian peatlands can be understood as a side effect of their re-equilibration after dissection by canals and ditches, and demonstrates how drainage network geometry can be taken into account when evaluating land-use impacts and mitigation strategies.

2. Materials and methods

2.1. Carbon storage capacity

To evaluate the capacity of tropical peatland drainage networks to store carbon, we used an equation derived in [25] that relates equilibrium peat dome morphology (figure 1) to the efficiency of lateral flow through peat, or transmissivity, $T$; time-averaged precipitation $P$; and evapotranspiration $ET$. This analysis showed that the curvature $\kappa$ of the peat surface, defined using the Laplacian of the peat surface elevation ($\kappa = -\nabla^2 p$), reaches an ecosystem- and climate-specific equilibrium curvature $\kappa_e$ given by $\kappa_e = \langle P - ET \rangle / \langle T \rangle$ where $\langle \rangle$ indicates time averaging (a brief derivation is provided in the appendix). The equation is based on the following approximations, supported by literature data: (1) peat oxidation increases with water table depth [40]; (2) there is a sharp increase in hydraulic transmissivity as the water table rises [32, 33], so that to a good approximation, transmissivity of the peat is a function only of the water level relative to the surface; and (3) the water level relative to the surface remains spatially uniform across the domed peatland even as it fluctuates with time [24].

Perhaps surprisingly, the form of the equilibrium peat morphology equation makes it possible to write a parcel’s maximum carbon storage $C$ as a product of independent factors describing the ecosystem and climate on one hand, and the geometry of the parcel boundary on the other

$$C = \frac{1}{8\pi} \rho_c \kappa_e SA^2,$$

(1)
Figure 1. Ecosystem feedback leading to a steady-state capacity for carbon storage in tropical peatlands. (a) Peat accumulates when organic matter is produced faster than it decomposes, mostly at the surface above the water table. At a certain mean water table, production of organic matter balances its decomposition in the aerobic zone. (b)–(d) A peat dome is at equilibrium when the gross curvature $\kappa$ of the peat surface has a certain value $\kappa^*$ such that the mean water table resides at its equilibrium position in the soil profile. (d)–(e) Effect of subdivision of peatland into smaller parcels by a ditch: equilibrium curvature is unchanged, but smaller parcels result in a lower mean peat height and therefore a lower capacity for carbon storage.

Figure 2. Maximum peat height in parcels of different shapes (b)–(g), from numerical solution of Poisson’s equation. (a) The maximum volume of peat that can be stored per area in a parcel can be broken down into the area of the parcel (horizontal axis) and a scale-independent parcel ‘shape factor’ (slope of line). Because of the smaller shape factor of a 4:1 rectangle than a square, the $\frac{1}{4}$ km$^2$ rectangular parcels in (g) cannot store as much carbon as the $\frac{1}{2}$ km$^2$ squares in (f), and creation of canals as $d \rightarrow e \rightarrow g$ results in the loss of more potential for carbon storage than creation of canals as $d \rightarrow e \rightarrow f$.

where the peat carbon density $\rho_c$ and equilibrium curvature $\kappa^*$ are determined by the ecosystem and climate [25]. The other terms $SA^2$ are purely geometric, and provide a climate- and ecosystem-independent measure of the capacity for carbon storage in a parcel relative to a 1 km$^2$ disk-shaped parcel in the same ecosystem and climate (appendix). The parcel shape factor $S$ is a scale-independent factor determined by the geometric shape of the parcel and $A$ is the parcel area (‘parcel’ refers to any channel-bounded area where peat accumulates). The parcel shape factor $S$ must be computed numerically for realistic shapes, but is independent of the parcel size; it is at most 1, for a disk (the shape that can support the highest water table in a fixed area), and approaches 0 in a parcel that is infinitesimally narrow (figure 2).

2.2. Analysis of parcel geometry in Borneo peatlands

To probe the distributions of peatland parcel areas $A$ and shape factors $S$ in real landscapes, we examined parcels created by artificial and natural drainage networks at sites in northwest and southern Borneo: in northwest Borneo, oil palm plantations near the Baram River (‘Baram’), and natural peat domes near the Belait River (‘Belait’); and in southern Borneo, an area drained for the ex-Mega Rice Project area (‘EMRP’), and natural peat domes near the Kat-ingan and Sebangau Rivers (‘Sebangau’; figure 3). At all four sites, peat domes were built up during the Holocene by floristically similar hardwood tropical peat swamp forests [8]. At the two sites in northwest Borneo (Baram and Belait), peat domes were initiated between about 5000 and 1000 cal BP [20], while the drainage network at the Belait site has not been altered. At the two sites in southern Borneo (EMRP and Sebangau), peat domes were initiated on
podzolic terraces between about 14 000 and 9 000 cal BP, during a period of increasing rainfall and rising sea levels [8]. The EMRP site was drained by large primary canals excavated beginning in 1995 as part of a large rice cultivation project. The project was subsequently abandoned [20] without construction of the network of field drains typical of plantation agriculture.

For each site, we digitized parcel boundaries using Google Earth (www.google.com/earth) at a resolution of about 100 m cm⁻¹, except for areas in southern Borneo without high-resolution images, where we used 200 m cm⁻¹. We demarcated parcels using visible streams and rivers where possible, excluding flooded forest that can occur at confluences and the edges of large rivers. In the Belait and Sebangau regions, we looked for parcels minimally affected by drainage, but used extant drainage boundaries, even if artificial. In some areas of the Sebangau region, artificial channels were indistinct because of a combination of lower-resolution imagery and land use and we instead drew the parcel boundary to exclude the general area that appeared drained. We used a geospatial data translator library (http://gdal.org) to convert each polygon to a suitable projected coordinate system (EPSG:5247 GDBD2009 for northwest Borneo, EPSG:32 749 WGS 84 / UTM zone 49S for southern Borneo) and load it into a spatial database (http://postgis.net), which we used to measure the area A of each polygon. We then generated a quadrilateral mesh inside each parcel [41] and solved Poisson’s equation on the mesh with a solver written in Cython (http://cython.org) using the deal.II finite-element library [42]. We then sampled the numerical solution (using VTK Python, http://vtk.org/) on a square grid chosen to give at least 2000 points within each polygon (grid spacing of 1 m, 8 m, 20 m, 70 m, and 100 m for Baram, EMRP, Belait, Badas, and Sebangau regions, respectively) to determine the shape factor S (figure 4(a)).

2.3. Carbon capacity in a peat dome cut by a canal
As an example of the effect of a canal on peatland carbon storage capacity, we examined a site in northwest Borneo where a large peat dome, the Badas peat dome, was divided by a canal before 1972. To calculate the carbon storage capacity of the Badas peat dome before and after its drainage by the canal, we drew a boundary around the entire dome and then around the two smaller parcels created by the canal using Google Earth, as described above. We then solved Poisson’s equation on the pre-canal parcel and the two post-canal parcels, and evaluated the limiting dome volume as done for other parcels. We used the equilibrium peat surface curvature \( \kappa_e = 2.36 \times 10^{-3} \) km⁻¹ from an earlier topographic analysis of a peat dome 7 km to the south [33], which hosts the same monodominant forest types and has the same developmental history as the other Belait domes [23]. The total limiting volume of each dome above the drainage network was calculated as the area of the boundary polygon multiplied by the mean limiting peat elevation from solving Poisson’s equation, sampled every 70 m on an east-west, north-south grid as described above. Finally, we estimated the total carbon storage capacity of the pre- and post-canal drainage boundaries at this site by multiplying the pre- and post-canal volumes by the carbon density \( \rho_c = 35 \text{ kg m}^{-2} \) [43] measured in cores taken from the same dome used for estimation of equilibrium peat surface curvature.

3. Results and discussion
Our analysis shows how the partitioning of a peatland into parcels by a drainage network constrains its capacity for peat accumulation (figures 1 and 2). In practice, plantation parcels are much smaller than natural peat domes (figure 3): in the peatlands we examined in northwest Borneo, plantation parcels are smaller in mean area than natural parcels in nearby undrained peatlands by a factor of more than 7180 (0.005 65 vs. 40.6 km²). The plantation parcels also have smaller shape factors because they are long and narrow (mean \( S = 0.277 \) vs. 0.667). Thus the mean equilibrium peat height in natural peat dome parcels of the Belait district is 3.19 m and their carbon storage capacity per area averages 125 kg C m⁻², whereas the mean equilibrium peat height above drainage boundaries in the Baram plantation parcels is less than 1 mm, and their capacity to store carbon above the drainage network is negligible (less than 6 g C m⁻²). The negligible capacity of these plantation parcels for carbon storage above the drainage network reflects the almost complete oxidation of carbon stocks that will occur in the long term if these drainage networks are maintained.

The studied parcels in the EMRP area in southern Borneo are exceptionally large (figure 3) because the area was never developed for large-scale plantation agriculture [20], and are more isodiametric in shape (mean \( S = 0.686 \) ) than the natural parcels of Sebangau (mean \( S = 0.475 \) ). Nonetheless, on a geometric basis alone, the carbon storage capacity per area in the Sebangau domes is larger on average by a factor of 76.4 (522 vs. 6.83) because of their vastly greater size (mean parcel area 1370 km² vs. 6.86 km²).

Analysis of parcels in the four sample peatlands shows that while a parcel’s shape affects its capacity for carbon storage, parcel area ranges over more than 6 orders of magnitude (0.002 0–4087 km²), and therefore has a dominant effect on parcel storage capacity (figure 4). By definition, the parcel shape factor cannot exceed a value of 1, but can be arbitrarily small. Thus, in principle, a parcel the size of our largest (4087 km²) could have a smaller capacity than our smallest (0.002 km²), if the large parcel were sufficiently long and thin (shape factor less than \( 5 \times 10^{-7} \)). In practice, the largest parcel shape
factor measured (0.966) was 6.14 times the smallest (0.157, figure 4(c)). Thus, although the precise shape factor for a complex parcel can only be computed numerically, the relative capacity of two networks in the same climate and ecosystem can be roughly estimated based on just parcel area: maximum peat volume scales with total peatland area times mean parcel area. If a dome is cut into one hundred parcels of similar shape, the maximum volume of each parcel will be roughly 0.01% of the dome’s original limiting volume, and the total carbon storage capacity of the parcels will be roughly 1% that of the original dome.

Our analysis of carbon storage capacity separates the effects of drainage network geometry from ecosystem and climate (equation (1)). In different regions and ecosystems, peat carbon density may vary; for example, published data suggest that typical carbon densities in the southern Borneo sites are about 40% higher than in coastal peatlands of Borneo and Sumatra (61 vs. 44 kg m$^{-3}$ [8]). Limiting peat surface curvatures $\kappa^*$ are likely to differ too because of contrasts in rainfall patterns, peat hydraulic conductivity, peatland productivity and decomposition rates [25]. Thus, to compare natural carbon storage capacities across regions and ecosystems, an estimate of the limiting peat surface curvature using the methods of Cobb et al [25] is required as well, preferably from topographic data with a high vertical resolution. For example, although the parcels of the Sebangau region have a maximum volume per area 15.4 times that of...
Parcel shape, size, and relative maximum peat volume per area in tropical peatlands in natural and artificial drainage networks. (a) Calculation of relative maximum peat volume per area $\gamma$ and shape factor $S$. (b) Parcel maximum peat volume per area, relative to a 1 km$^2$ disk-shaped parcel, vs. parcel area. Guides show the lowest shape factor observed (0.157) and the largest shape factor possible (1, disk). (c) Box plot of parcel shape factors, annotated with sample parcel outlines.

Figure 4. Parcel shape, size, and relative maximum peat volume per area in tropical peatlands in natural and artificial drainage networks. (a) Calculation of relative maximum peat volume per area $\gamma$ and shape factor $S$. (b) Parcel maximum peat volume per area, relative to a 1 km$^2$ disk-shaped parcel, vs. parcel area. Guides show the lowest shape factor observed (0.157) and the largest shape factor possible (1, disk). (c) Box plot of parcel shape factors, annotated with sample parcel outlines.
Figure 5. Reduction of capacity for carbon storage in a peatland by a canal. (a) Location of Badas peat dome in northwest Borneo (see Figure 3(b) for regional map). (b) SRTM image of site, showing canal. (c),(d) Equilibrium shape of dome before division by canal (e) shows side view). (e),(f) Equilibrium shape of domes on two parcels created by canal. (g) Reduction in peatland carbon storage capacity by canal because of change in equilibrium shape. Map data: Esri, Wetlands International, NASA.

Sebangau, the EMRP parcels would approach their equilibrium morphologies in very roughly 0.08% of the time that would be required to completely destroy the equilibrium relief of the original domes. The faster equilibration of the small parcels created by canals in the EMRP is apparent in high-resolution topographic data from the area [47], which show a domed morphology in each EMRP parcel superimposed on a large natural dome that will gradually disappear from peat loss to decomposition and fire.

As parcels become very large, processes in peat domes may begin to deviate from the approximations underlying the theory we apply. Flow through deeper peat will account for an increasing proportion of the water budget in larger domes, and could begin to limit carbon storage because water is effectively drained from the dome interior to its edges through the deep peat [48]. Anaerobic decomposition in peat below the water table could also begin to limit height in sufficiently large domes [49], though available evidence suggests that anaerobic decomposition is extremely slow in tropical peats [8]. These refinements would predict a ‘leveling-off’ of the storage capacity vs. area curve due to the leveling-off mechanism we have just described. Whatever the model for equilibrium bog shape, a storage capacity analysis would bring the same strengths and weaknesses in northern peatlands as in the tropics: it would not predict instantaneous fluxes or detailed dynamics, but would provide spatially explicit predictions of long-term impact, and complement an emission factor approach by describing how much carbon can be preserved in the long term under different management scenarios.

4. Conclusions

Tropical peat domes progressively sequester carbon as waterlogged organic matter over thousands of years. Classic studies explored how the hydrologic-ecosystem feedback that drives peat accumulation also limits the height and shape of raised bog cross-sections. Our analysis applies an analogous approach to landscapes, and shows the limiting shapes of tropical peat domes in three dimensions. The maps produced by this analysis convey intuition about not only how drainage networks constrain
the morphology of tropical peatlands, but also how re-configuration of these networks will transform peatland morphology over time. Although we do not analyze dynamics, our equilibrium model can be combined with typical rates of peat accumulation and loss to yield a rough lower bound on the time required for re-equilibration of a peatland after alteration of the drainage network. The approach can predict spatial patterns in decomposition and flammability, as well as the long-term effects of interventions such as blocking of peatland ditches and canals. Our analysis shows how the critical factors of parcel size and shape can be taken into account when designing mitigation strategies to arrest or reverse tropical peatland greenhouse gas emissions.

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Author contributions

ARC designed and performed research, and analyzed data; ARC, FT, and NHEH contributed new analytic tools; all authors contributed to writing of the manuscript.

Competing interests

The authors declare no competing interests.

Data availability statement

The data reported in this paper have been deposited in the PANGAEA open access data archive, doi:10.1594/PANGAEA.914130.

Appendix A.

Here we provide brief derivations of the peat morphology equilibrium equation and the scaling principles applied in our analysis.

A.1. Equilibrium peat morphology

In [25], we derived a peat equilibrium morphology equation from Boussinesq’s equation for water table elevation \( H \) subject to precipitation \( P \) and evapotranspiration \( ET \)

\[
S_o \frac{\partial H}{\partial t} = P - ET + \nabla \cdot (T \nabla H),
\]

where both the specific yield \( S_o(\zeta) \) and the transmissivity \( T(\zeta) \) are functions of the local water level \( \zeta \), defined as the elevation of the water table \( H \) relative to the surface \( p(\zeta = H - p) \). Because net peat loss shifts to net accumulation as the water level rises, there is a mean water level at which the rate of peat production by the ecosystem is balanced by the rate of decomposition in surface peat (figure 1). The peat surface morphology \( p \) that maintains a stationary and uniform water level \( \zeta \) is derived by substituting \( \zeta \) into the groundwater flow equation (A1) and setting the time-averaged change in local water storage \( \langle S_o \partial H/\partial t \rangle \) to zero

\[
0 = \langle P - ET \rangle + \nabla \cdot \langle T \nabla (p + \zeta) \rangle.
\]

The water level \( \zeta \) is approximately spatially uniform, so its gradient \( \nabla \zeta \) is zero. The transmissivity \( T \) is also approximately uniform and is independent of \( p \), so it can be moved outside the divergence operator \( \nabla \cdot \), yielding the equilibrium peat morphology equation

\[-\nabla^2 p = \kappa_e \]

We first describe the carbon capacity of a disk-shaped parcel, which we use as a reference for other calculations. The shape of a surface with uniform Laplacian \( \nabla^2 p = -\kappa_e \) above a flat, circular boundary with radius \( R \) is a parabolic dome with equation \( p = \kappa_e \left(R^2 - r^2\right)/4 \). The limiting volume \( V_o \) of this reference dome can be calculated by integration as

\[V_o = \pi \kappa_e R^3/8.\]

Substituting in the area of the parcel \( A = \pi R^2 \), the limiting volume of the dome inside can equivalently be written \( V_o = \kappa_e A^2/(8\pi) \). The carbon capacity \( C_o \) of this disk-shaped parcel is the peat carbon density \( \rho_c \) times the limiting peat volume,

\[C_o = \frac{1}{8\pi} \rho_c \kappa_e A^2.\]
peat $p$ above the boundary elevation is described by Poisson’s equation $-\nabla^2 p = \kappa_s$. Suppose we stretch the peat surface $p$ vertically by a factor $c$ to a new shape described by $p' = c p$. By the definition of the Laplacian,

$$-\kappa_s = \nabla^2 p' = \frac{\partial^2 p'}{\partial x^2} + \frac{\partial^2 p'}{\partial y^2} = -c \kappa_s,$$

so we have scaled the curvature by the factor $c$. At the same time, we have increased the mean surface height by the same factor ($p' = c p$) without altering the parcel area. Thus, the limiting peat volume $V = \overline{p} A$ on this arbitrarily-shaped parcel and its carbon capacity $C = \rho_c V$ are proportional to the equilibrium peat surface curvature $\kappa_s$.

Now consider the effect of stretching the dome footprint isotropically to a larger but geometrically similar area $A' = c A$, but with the same curvature $\nabla^2 p' = \kappa_s$. We achieve this stretching by scaling the coordinate system by the square root of this factor, $x' = \sqrt{c} x$, $y' = \sqrt{c} y$. First, we show that we can preserve the curvature $\nabla^2 p' = -\kappa_s$. If the peat surface height $p'(x', y') = c p(x, y)$ is scaled by the same factor $c$ as the area:

$$\nabla^2 p' = \frac{\partial^2 p'}{\partial x'^2} + \frac{\partial^2 p'}{\partial y'^2} = \frac{c}{\partial x^2} + \frac{c}{\partial y^2} = -\kappa_s.$$

Now we compute the mean peat surface height of the stretched dome:

$$p' = \frac{\iint p' \, dA'}{A'} = \frac{c^2 \iint p \, dA}{c A} = c \overline{p}.$$

Thus the limiting peat volume $V' = A' \overline{p} = c^2 A \overline{p} = c^2 V$ has grown by the square of the factor $c$ by which we scaled the area.

**ORCID iDs**

Alexander R Cobb [https://orcid.org/0000-0002-3128-3002](https://orcid.org/0000-0002-3128-3002)
René Dommain [https://orcid.org/0000-0003-4547-8983](https://orcid.org/0000-0003-4547-8983)
Fangyi Tan [https://orcid.org/0000-0002-1831-5196](https://orcid.org/0000-0002-1831-5196)
Naomi Hwee En Heng [https://orcid.org/0000-0002-5363-4002](https://orcid.org/0000-0002-5363-4002)

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